# Parsing

borrowing from
Daniel Jurafsky and James Martin

# This chunk

- Parsing with CFGs
  - Bottom-up, top-down
  - Ambiguity
  - CKY parsing

# Parsing

- Parsing with CFGs refers to the task of assigning proper trees to input strings
- Proper here means a tree that covers all and only the elements of the input and has an S at the top
- It doesn't actually mean that the system can select the correct tree from among all the possible trees

# Parsing

- As with everything of interest, parsing involves a search which involves the making of choices
- We'll start with some basic (meaning bad) methods before moving on to the one or two that you need to know

# For Now

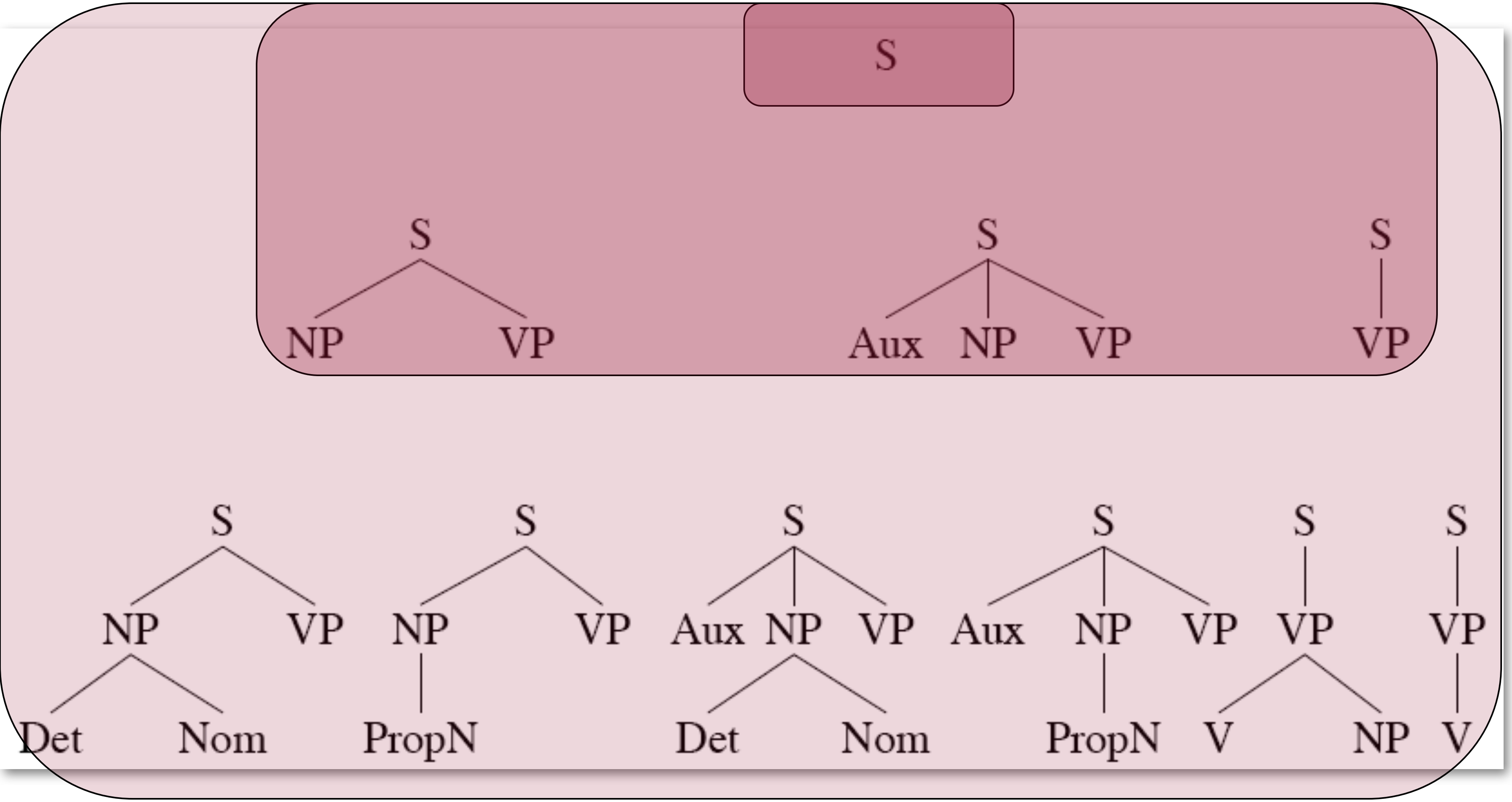
- Assume…
  - You have all the words already in some buffer
  - The input isn't POS tagged
  - We won't worry about morphological analysis
  - All the words are known

  - These are all problematic in various ways, and would have to be addressed in real applications.

# Top-Down Search

- Since we’re trying to find trees rooted with an S (Sentences), why not start with the rules that give us an S.
- Then we can work our way down from there to the words.

# Top Down Space



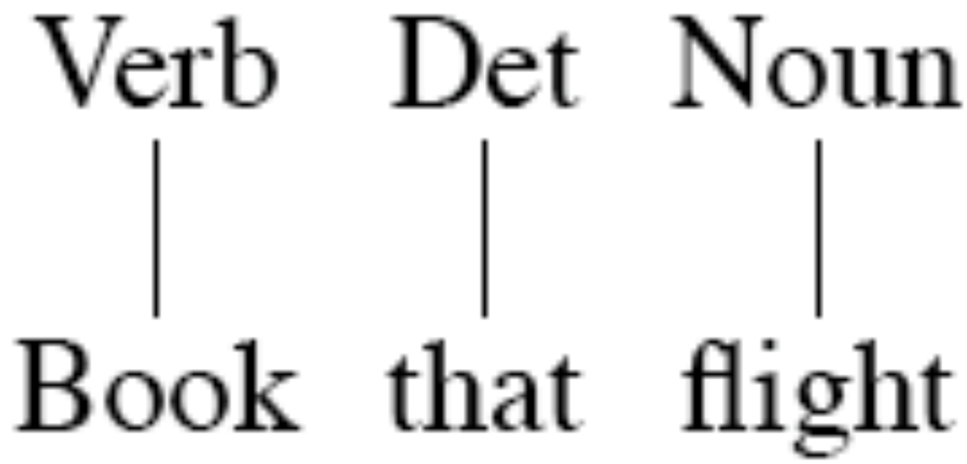
# Bottom-Up Parsing

- Of course, we also want trees that cover the input words. So we might also start with trees that link up with the words in the right way.
- Then work your way up from there to larger and larger trees.

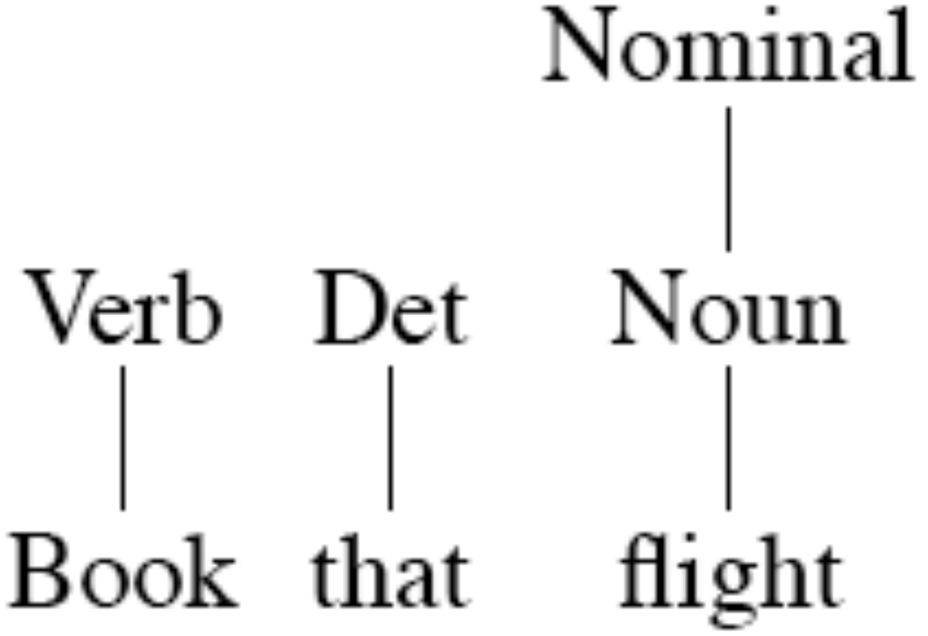
# Bottom-Up Search

Book that flight

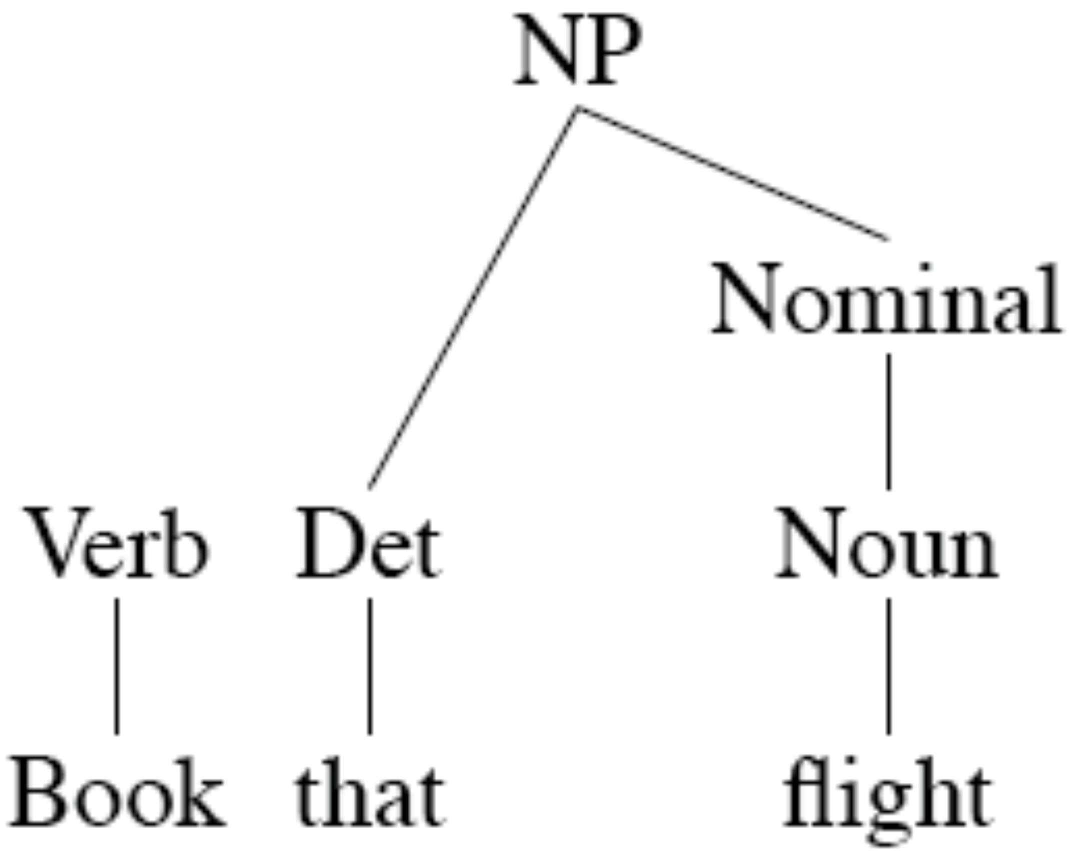
# Bottom-Up Search



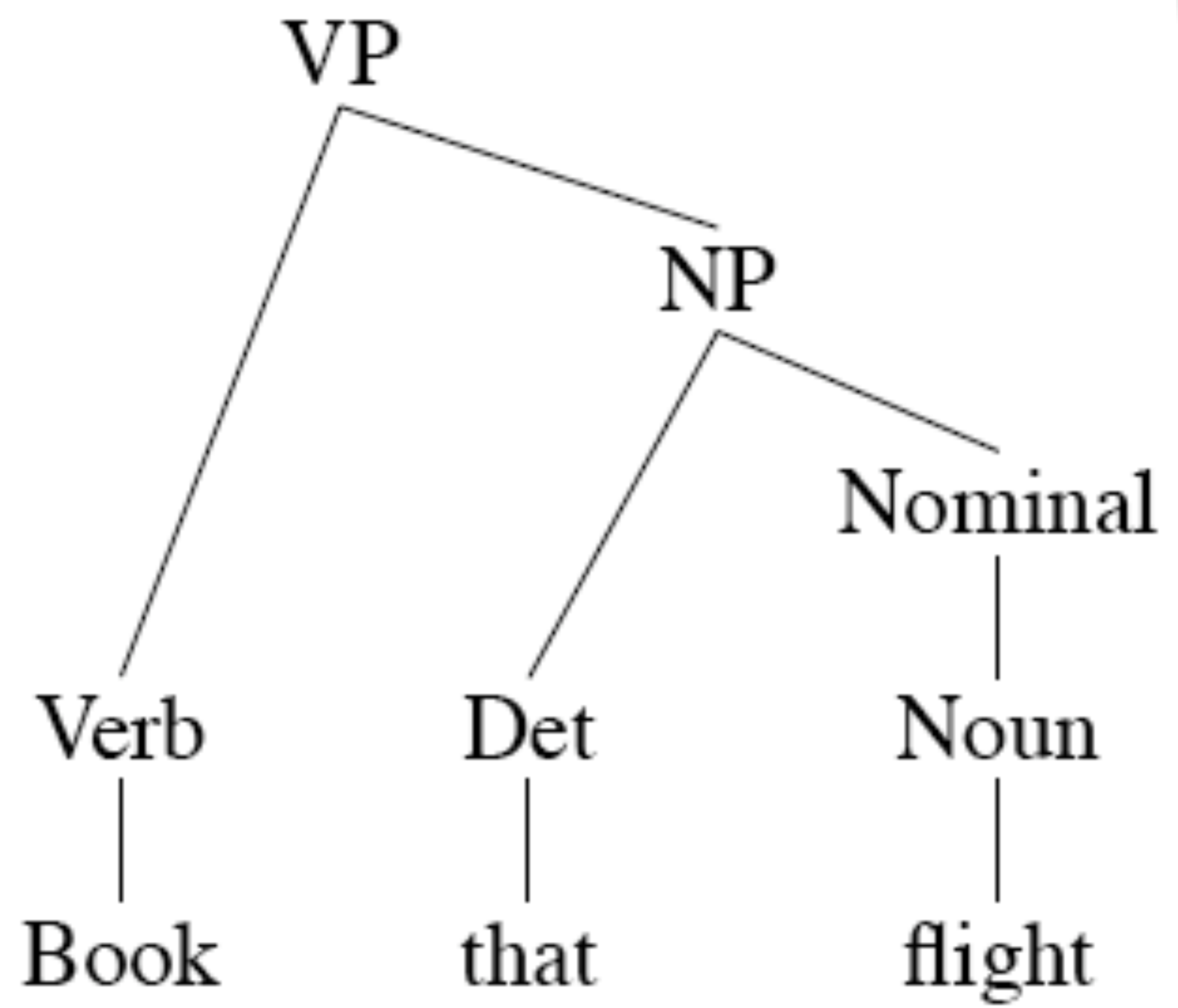
# Bottom-Up Search



# Bottom-Up Search



# Bottom-Up Search



# Top-Down and Bottom-Up

- Top-down
  - Only searches for trees that can be answers (i.e. S’s)
  - But also suggests trees that are not consistent with any of the words
- Bottom-up
  - Only forms trees consistent with the words
  - But suggests trees that make no sense globally

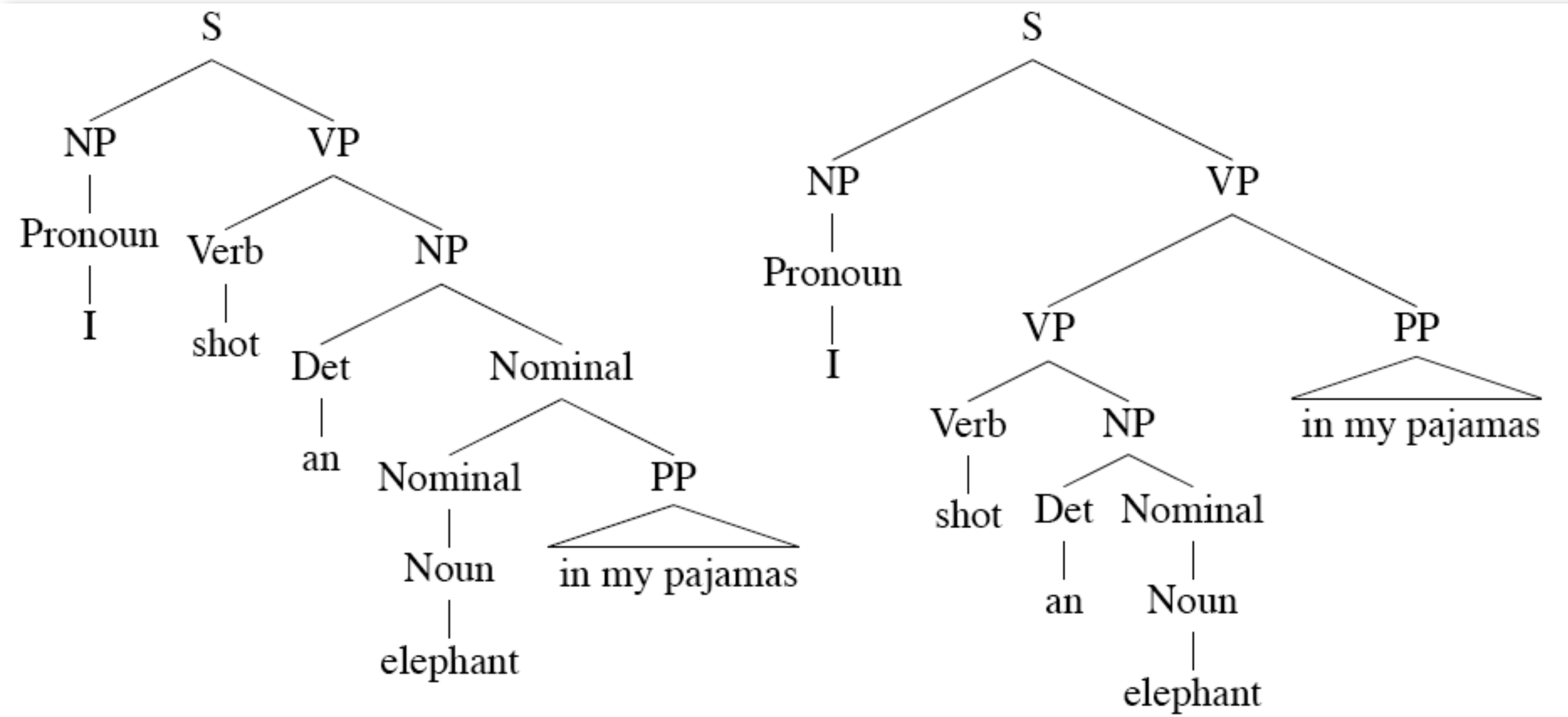
# Control

- Of course, in both cases we left out how to keep track of the search space and how to make choices
  - Which node to try to expand next
  - Which grammar rule to use to expand a node
- One approach is called backtracking.
  - Make a choice, if it works out then fine
  - If not then back up and make a different choice

# Problems

- Even with the best filtering, backtracking methods are doomed because of two inter-related problems
  - Ambiguity
  - Shared subproblems

# Ambiguity

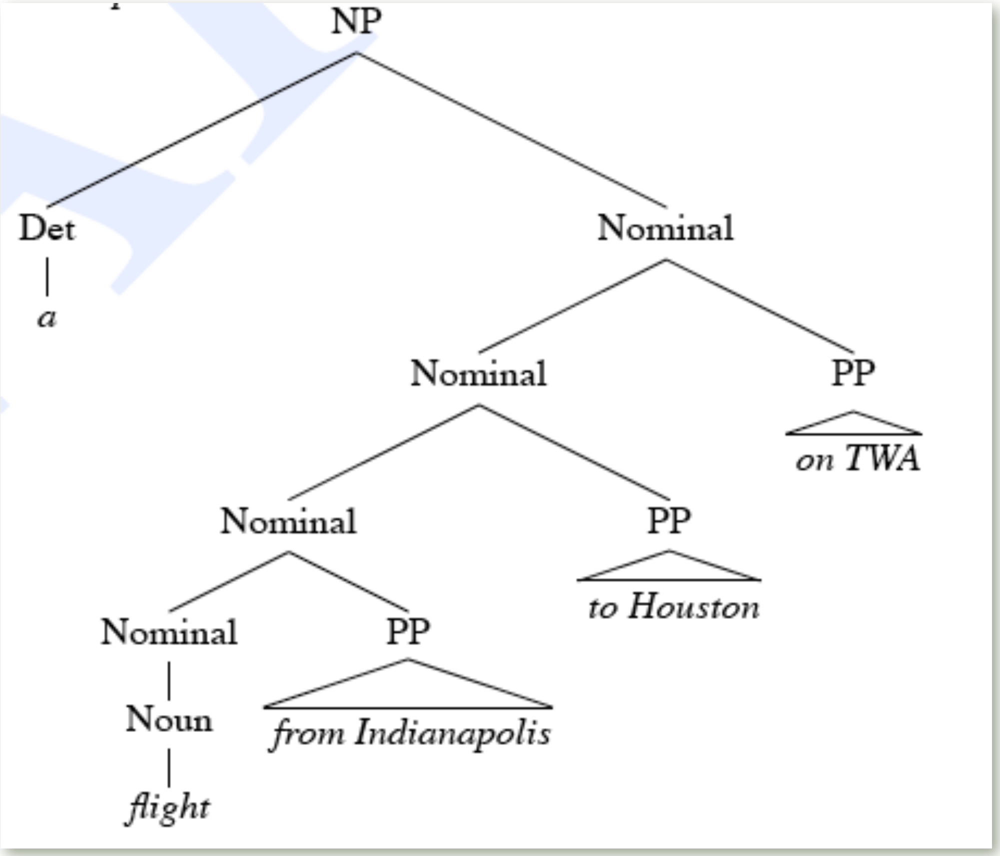

S
NP
VP
Pronoun
Verb
NP
I
shot
Det
Nominal
an
Nominal
PP
Noun
in my pajamas
elephant
S
NP
VP
Pronoun
VP
PP
I
Verb
NP
in my pajamas
shot
Det
Nominal
an
Noun
elephant

# Shared Sub-Problems

- No matter what kind of search (top-down or bottom-up or mixed) that we choose.
  - We don’t want to redo work we’ve already done.
  - Unfortunately, naïve backtracking will lead to duplicated work.

# Shared Sub-Problems

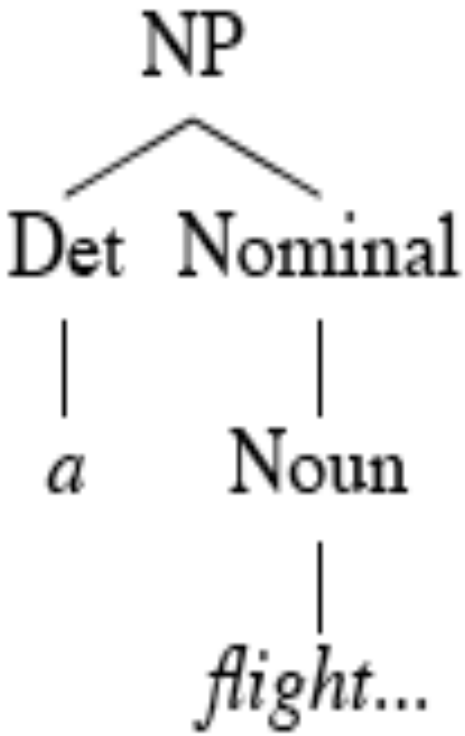
- Consider
  - A flight from Indianapolis to Houston on TWA



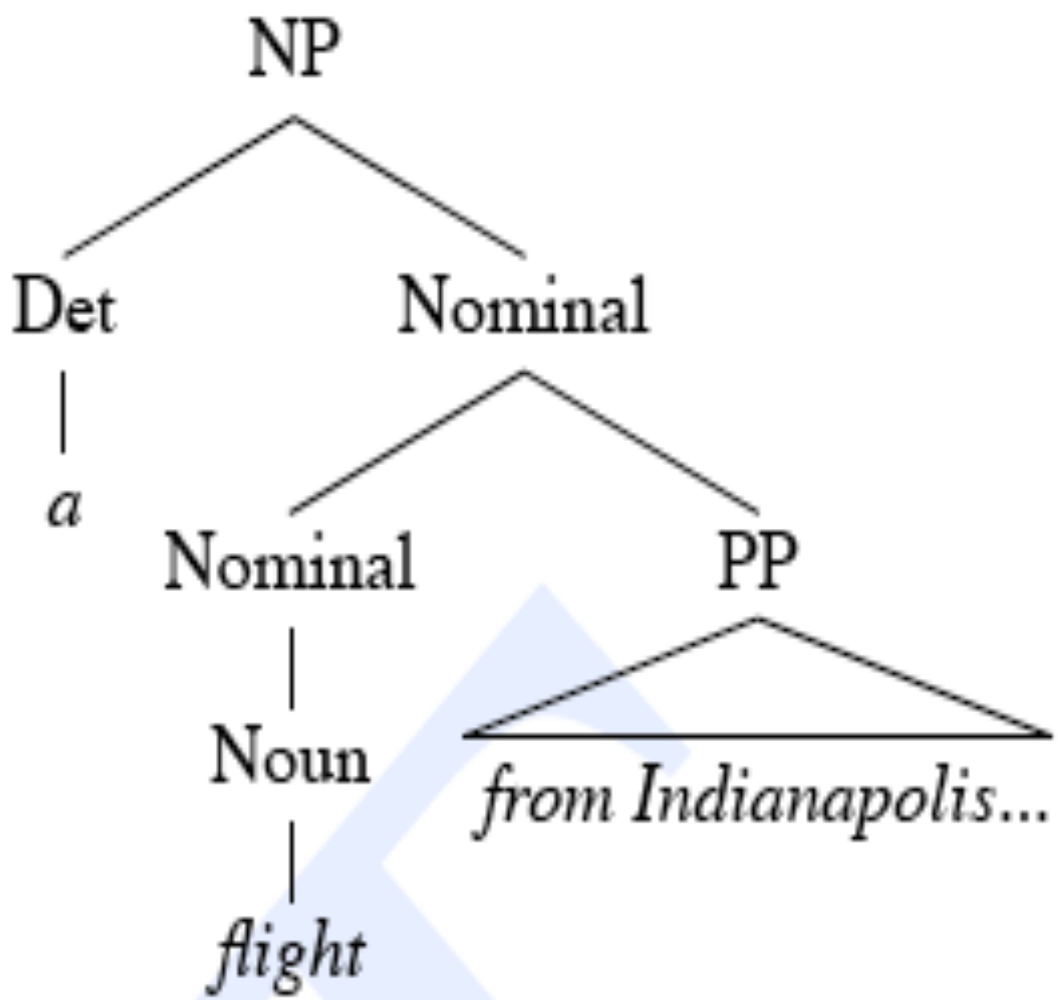
# Shared Sub-Problems

- Assume a top-down parse making choices among the various Nominal rules.
- In particular, between these two
  - Nominal -> Noun
  - Nominal -> Nominal PP
- Statically choosing the rules in this order leads to the following bad results...

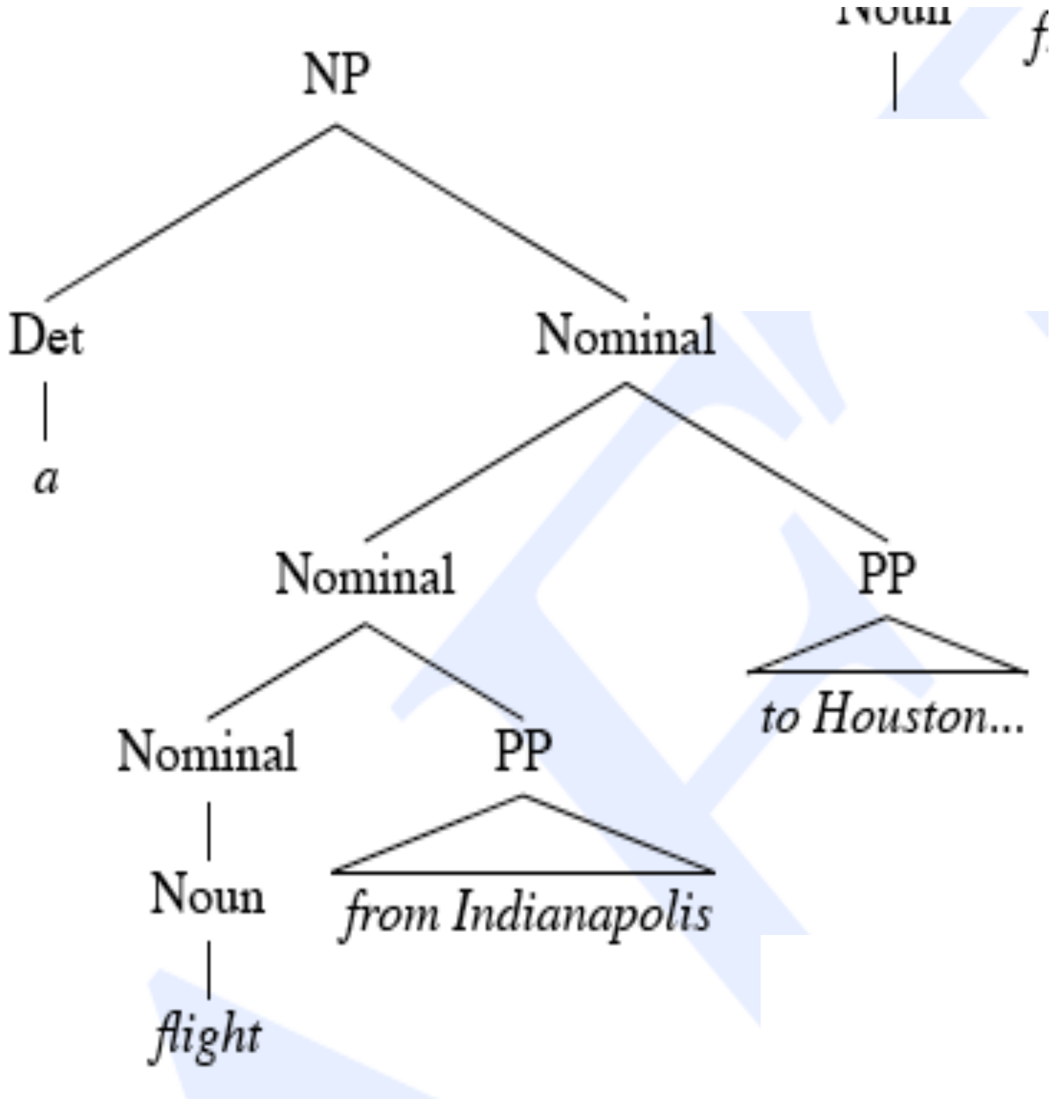
# Shared Sub-Problems



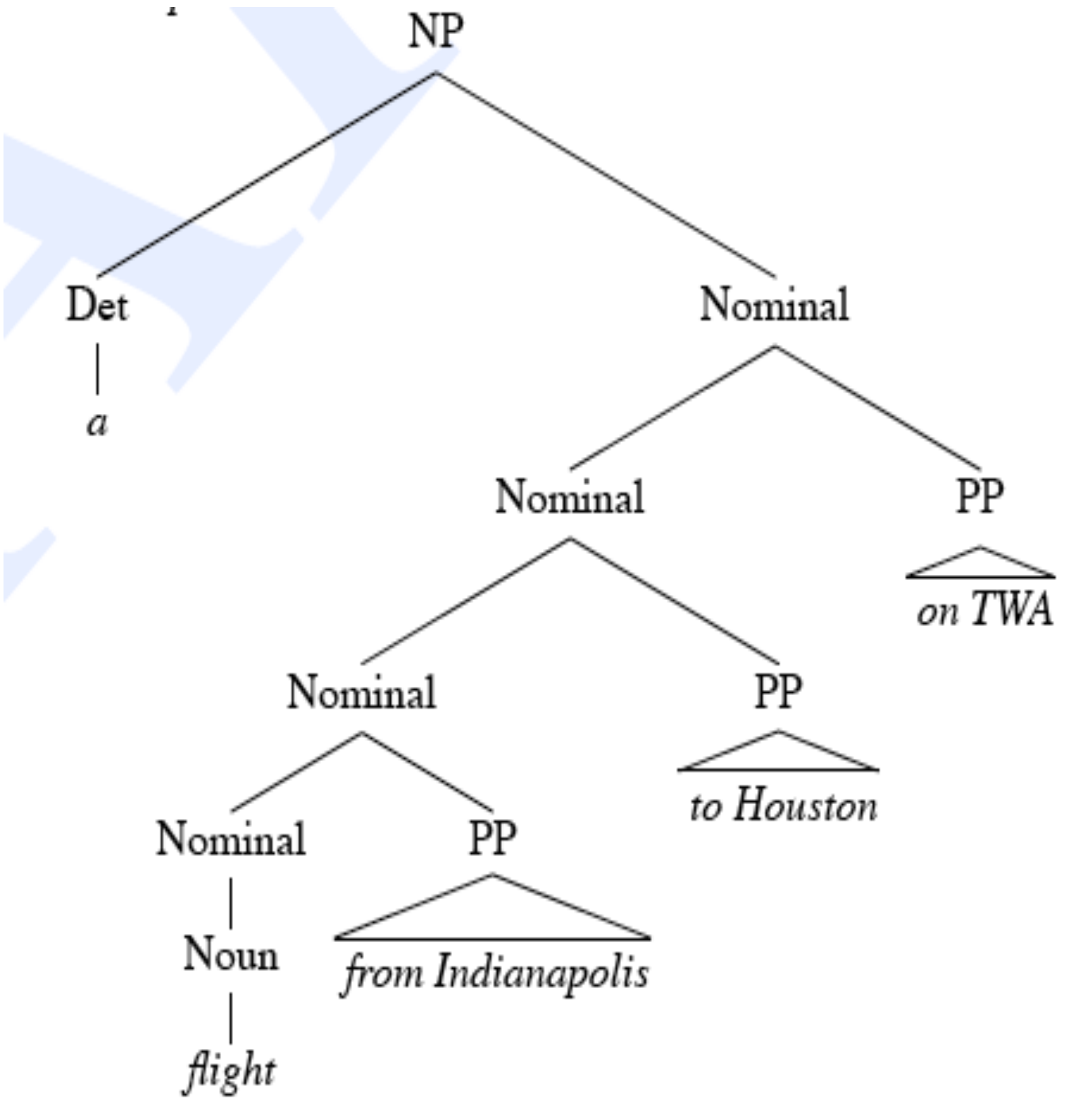
# Shared Sub-Problems



# Shared Sub-Problems



# Shared Sub-Problems



# Dynamic Programming

- DP search methods fill tables with partial results and thereby
  - Avoid doing avoidable repeated work
  - Solve exponential problems in polynomial time (well, no not really)
  - Efficiently store ambiguous structures with shared sub-parts.
- We'll cover two approaches that roughly correspond to top-down and bottom-up approaches.
  - CKY
  - Earley

# CKY Parsing

- First we'll limit our grammar to epsilon-free, binary rules (more later)
- Consider the rule $A \rightarrow BC$
  - If there is an A somewhere in the input then there must be a B followed by a C in the input.
  - If the A spans from i to j in the input then there must be some k st. $i<k<j$
    - Ie. The B splits from the C someplace.

# Problem

- What if your grammar isn't binary?
  - As in the case of the TreeBank grammar?
- Convert it to binary… any arbitrary CFG can be rewritten into Chomsky-Normal Form automatically.
- What does this mean?
  - The resulting grammar accepts (and rejects) the same set of strings as the original grammar.
  - But the resulting derivations (trees) are different.

# Problem

- More specifically, we want our rules to be of the form

  $A \rightarrow B\ C$

  Or

  $A \rightarrow w$

  That is, rules can expand to either 2 non-terminals or to a single terminal.

# Binarization Intuition

- Eliminate chains of unit productions.
- Introduce new intermediate non-terminals into the grammar that distribute rules with length > 2 over several rules.
  - So… S → A B C turns into

S → X C and

X → A B

Where X is a symbol that doesn't occur anywhere else in the the grammar.

# Sample L1 Grammar

| Grammar | Lexicon |
|---|---|
| $S \rightarrow NP\ VP$ | $Det \rightarrow that \mid this \mid a$ |
| $S \rightarrow Aux\ NP\ VP$ | $Noun \rightarrow book \mid flight \mid meal \mid money$ |
| $S \rightarrow VP$ | $Verb \rightarrow book \mid include \mid prefer$ |
| $NP \rightarrow Pronoun$ | $Pronoun \rightarrow I \mid she \mid me$ |
| $NP \rightarrow Proper\text{-}Noun$ | $Proper\text{-}Noun \rightarrow Houston \mid NWA$ |
| $NP \rightarrow Det\ Nominal$ | $Aux \rightarrow does$ |
| $Nominal \rightarrow Noun$ | $Preposition \rightarrow from \mid to \mid on \mid near \mid through$ |
| $Nominal \rightarrow Nominal\ Noun$ | |
| $Nominal \rightarrow Nominal\ PP$ | |
| $VP \rightarrow Verb$ | |
| $VP \rightarrow Verb\ NP$ | |
| $VP \rightarrow Verb\ NP\ PP$ | |
| $VP \rightarrow Verb\ PP$ | |
| $VP \rightarrow VP\ PP$ | |
| $PP \rightarrow Preposition\ NP$ | |

# CNF Conversion

| $\mathscr{L}_1$ **Grammar** | $\mathscr{L}_1$ **in CNF** |
|---|---|
| $S \rightarrow NP\ VP$ | $S \rightarrow NP\ VP$ |
| $S \rightarrow Aux\ NP\ VP$ | $S \rightarrow X1\ VP$ |
| | $X1 \rightarrow Aux\ NP$ |
| $S \rightarrow VP$ | $S \rightarrow book \mid include \mid prefer$ |
| | $S \rightarrow Verb\ NP$ |
| | $S \rightarrow X2\ PP$ |
| | $S \rightarrow Verb\ PP$ |
| | $S \rightarrow VP\ PP$ |
| $NP \rightarrow Pronoun$ | $NP \rightarrow I \mid she \mid me$ |
| $NP \rightarrow Proper\text{-}Noun$ | $NP \rightarrow TWA \mid Houston$ |
| $NP \rightarrow Det\ Nominal$ | $NP \rightarrow Det\ Nominal$ |
| $Nominal \rightarrow Noun$ | $Nominal \rightarrow book \mid flight \mid meal \mid money$ |
| $Nominal \rightarrow Nominal\ Noun$ | $Nominal \rightarrow Nominal\ Noun$ |
| $Nominal \rightarrow Nominal\ PP$ | $Nominal \rightarrow Nominal\ PP$ |
| $VP \rightarrow Verb$ | $VP \rightarrow book \mid include \mid prefer$ |
| $VP \rightarrow Verb\ NP$ | $VP \rightarrow Verb\ NP$ |
| $VP \rightarrow Verb\ NP\ PP$ | $VP \rightarrow X2\ PP$ |
| | $X2 \rightarrow Verb\ NP$ |
| $VP \rightarrow Verb\ PP$ | $VP \rightarrow Verb\ PP$ |
| $VP \rightarrow VP\ PP$ | $VP \rightarrow VP\ PP$ |
| $PP \rightarrow Preposition\ NP$ | $PP \rightarrow Preposition\ NP$ |

# CKY

- So let's build a table so that an A spanning from i to j in the input is placed in cell [i,j] in the table.
- So a non-terminal spanning an entire string will sit in cell [0, n]
  - Hopefully an S
- If we build the table bottom-up, we'll know that the parts of the A must go from i to k and from k to j, for some k.

# CKY

- Meaning that for a rule like $A \rightarrow B\ C$ we should look for a B in [i,k] and a C in [k,j].
- In other words, if we think there might be an A spanning i,j in the input… AND

  $A \rightarrow B\ C$ is a rule in the grammar THEN
- There must be a B in [i,k] and a C in [k,j] for some i<k<j

# CKY

- So to fill the table loop over the cell[i,j] values in some systematic way
  - What constraint should we put on that systematic search?
  - For each cell, loop over the appropriate k values to search for things to add.

# CKY Algorithm

**function** CKY-PARSE(*words, grammar*) **returns** *table*

**for** $j \leftarrow$ **from** 1 **to** LENGTH(*words*) **do**

$table[j-1, j] \leftarrow \{A \mid A \rightarrow words[j] \in grammar\}$

**for** $i \leftarrow$ **from** $j-2$ **downto** 0 **do**

**for** $k \leftarrow i+1$ **to** $j-1$ **do**

$$table[i,j] \leftarrow table[i,j] \cup \{A \mid A \rightarrow BC \in grammar, B \in table[i,k], C \in table[k,j]\}$$

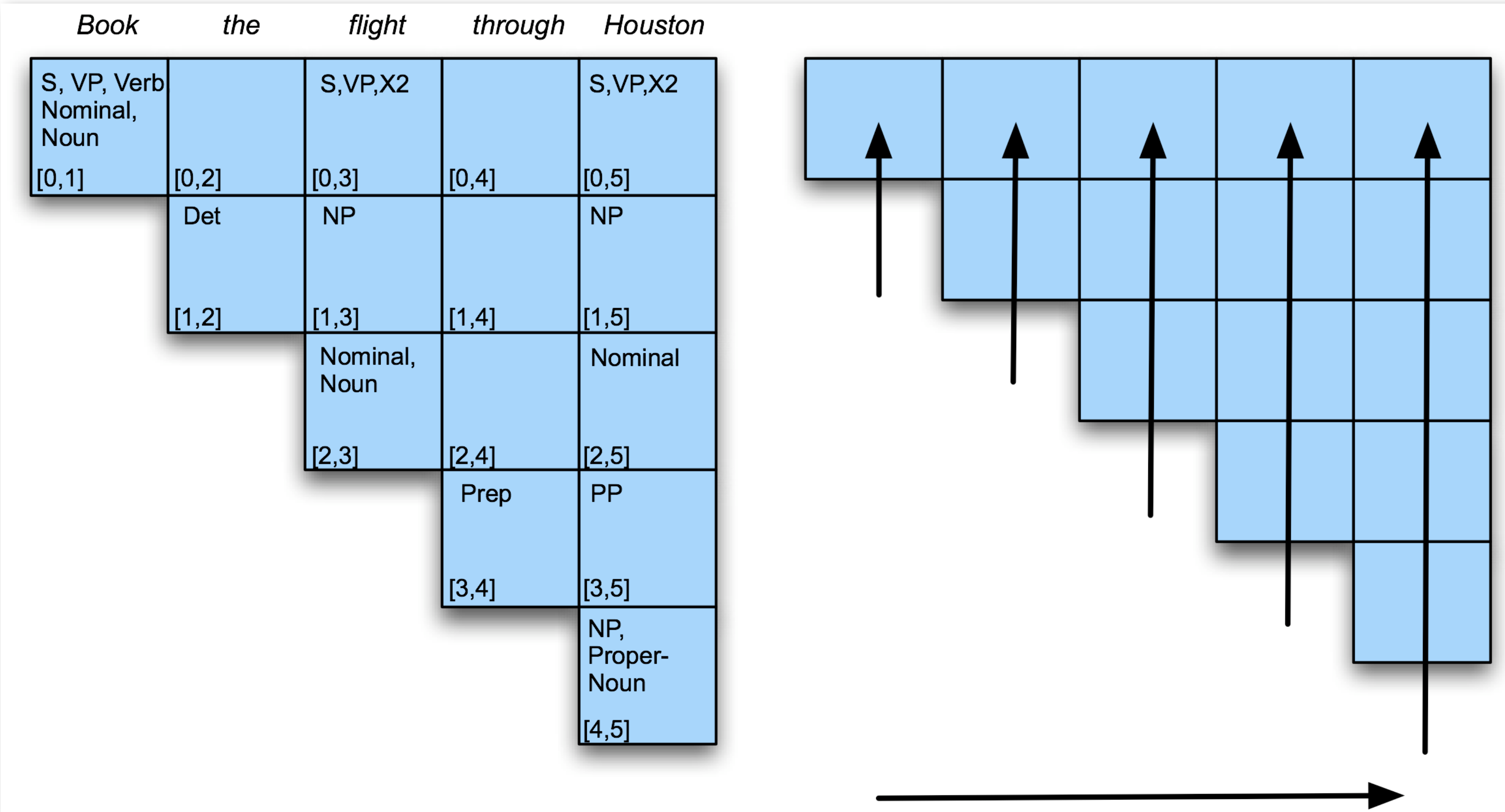
# CKY Parsing

- Is that really a parser?

# Note

- We arranged the loops to fill the table a column at a time, from left to right, bottom to top.
  - This assures us that whenever we're filling a cell, the parts needed to fill it are already in the table (to the left and below)
  - It's somewhat natural in that it processes the input a left to right a word at a time
    - Known as online

# Example

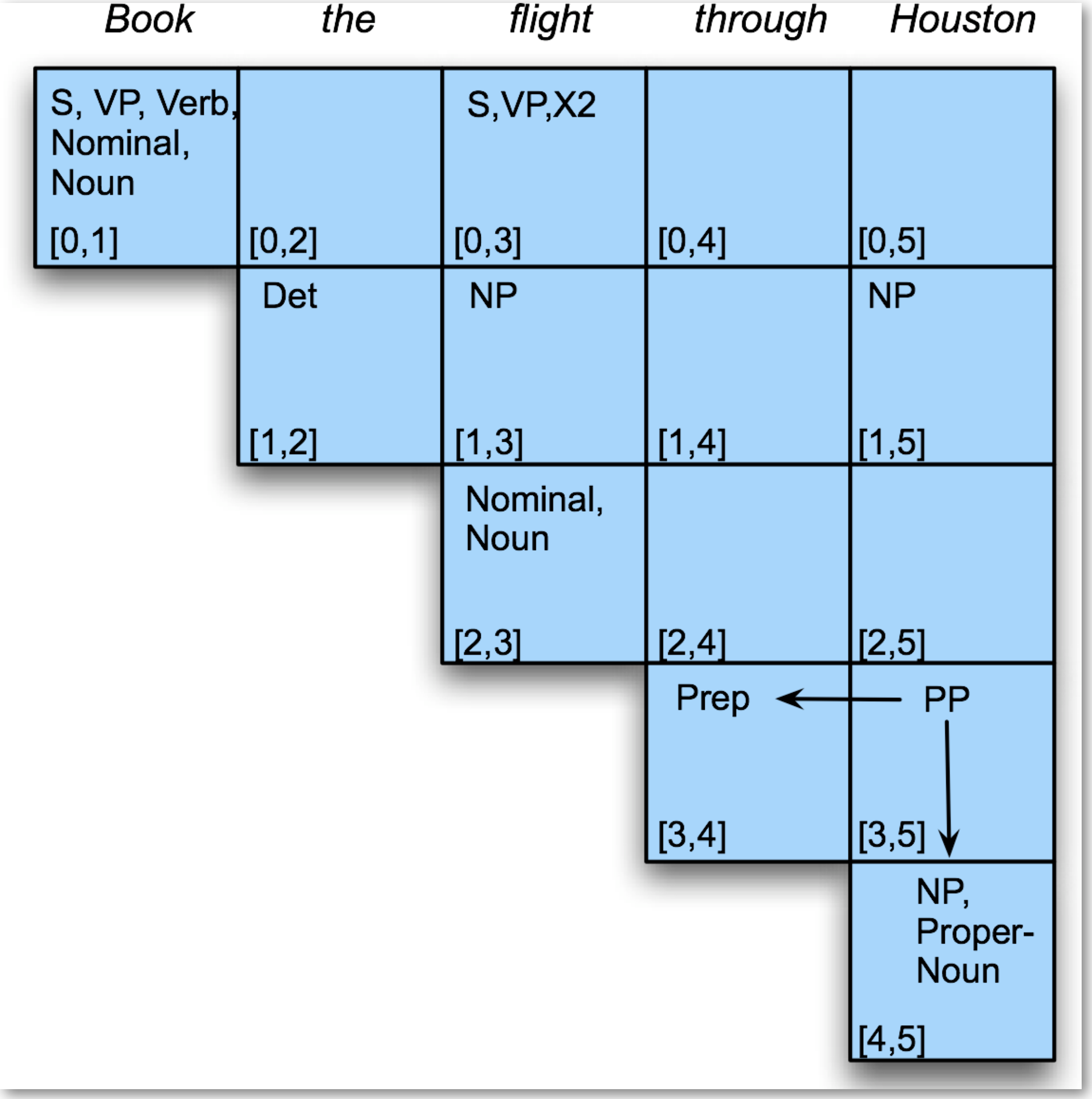

Book
the
flight
through
Houston
S, VP, Verb
Nominal,
Noun
[0,1]
[0,2]
S,VP,X2
[0,3]
[0,4]
S,VP,X2
[0,5]
Det
[1,2]
NP
[1,3]
[1,4]
NP
[1,5]
Nominal,
Noun
[2,3]
[2,4]
Nominal
[2,5]
Prep
[3,4]
PP
[3,5]
NP,
Proper-
Noun
[4,5]

# Example

| *Book* | *the* | *flight* | *through* | *Houston* |
|---|---|---|---|---|
| S, VP, Verb, Nominal, Noun [0,1] | [0,2] | S,VP,X2 [0,3] | [0,4] | [0,5] |
| | Det [1,2] | NP [1,3] | [1,4] | [1,5] |
| | | Nominal, Noun [2,3] | [2,4] | Nominal [2,5] |
| | | | Prep [3,4] | [3,5] |
| | | | | NP, Proper-Noun [4,5] |

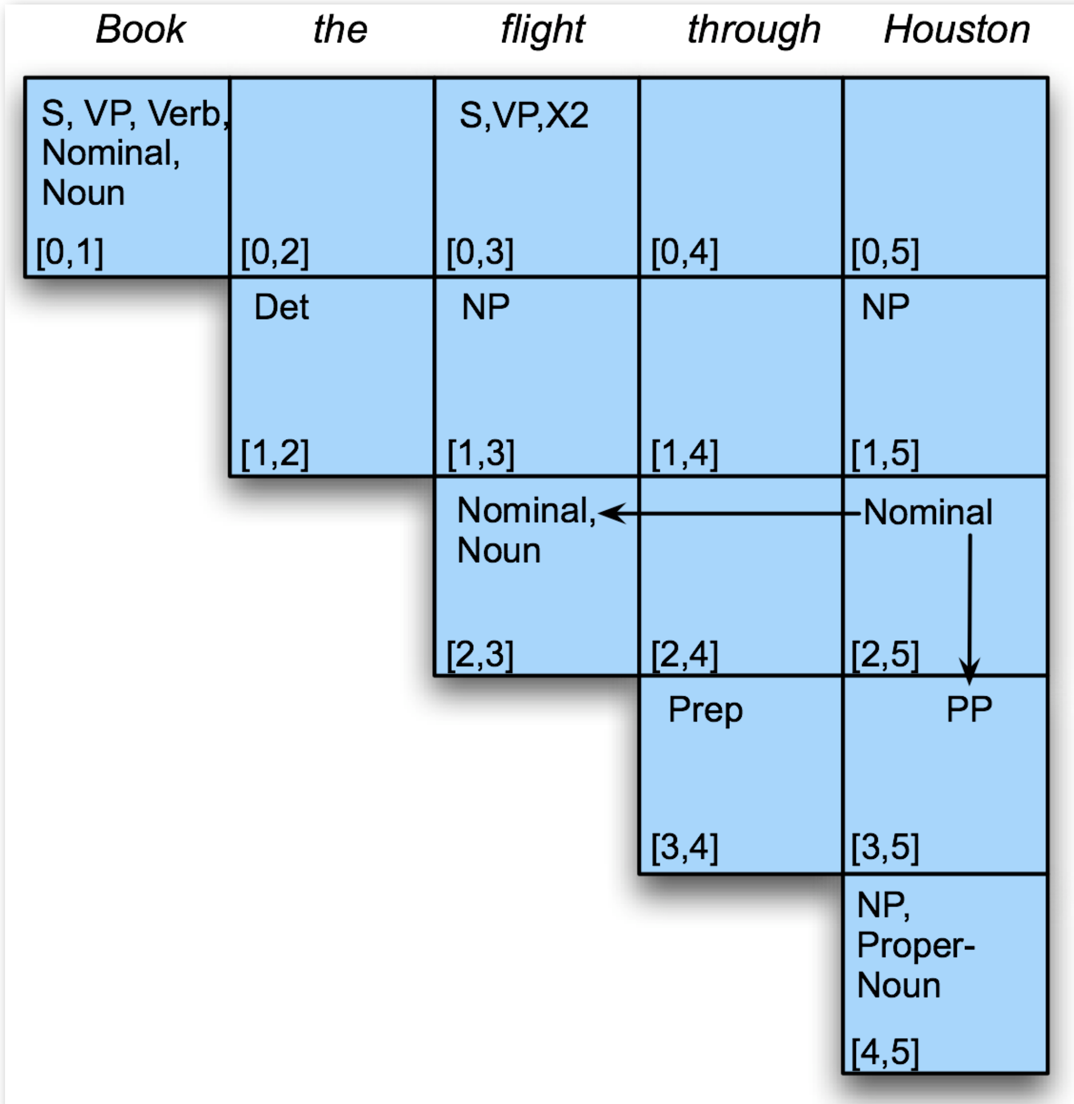
Filling column 5

# Example



Book
the
flight
through
Houston
S, VP, Verb, Nominal, Noun
[0,1]
[0,2]
S,VP,X2
[0,3]
[0,4]
[0,5]
Det
[1,2]
NP
[1,3]
[1,4]
NP
[1,5]
Nominal, Noun
[2,3]
[2,4]
[2,5]
Prep
[3,4]
PP
[3,5]
NP, Proper-Noun
[4,5]

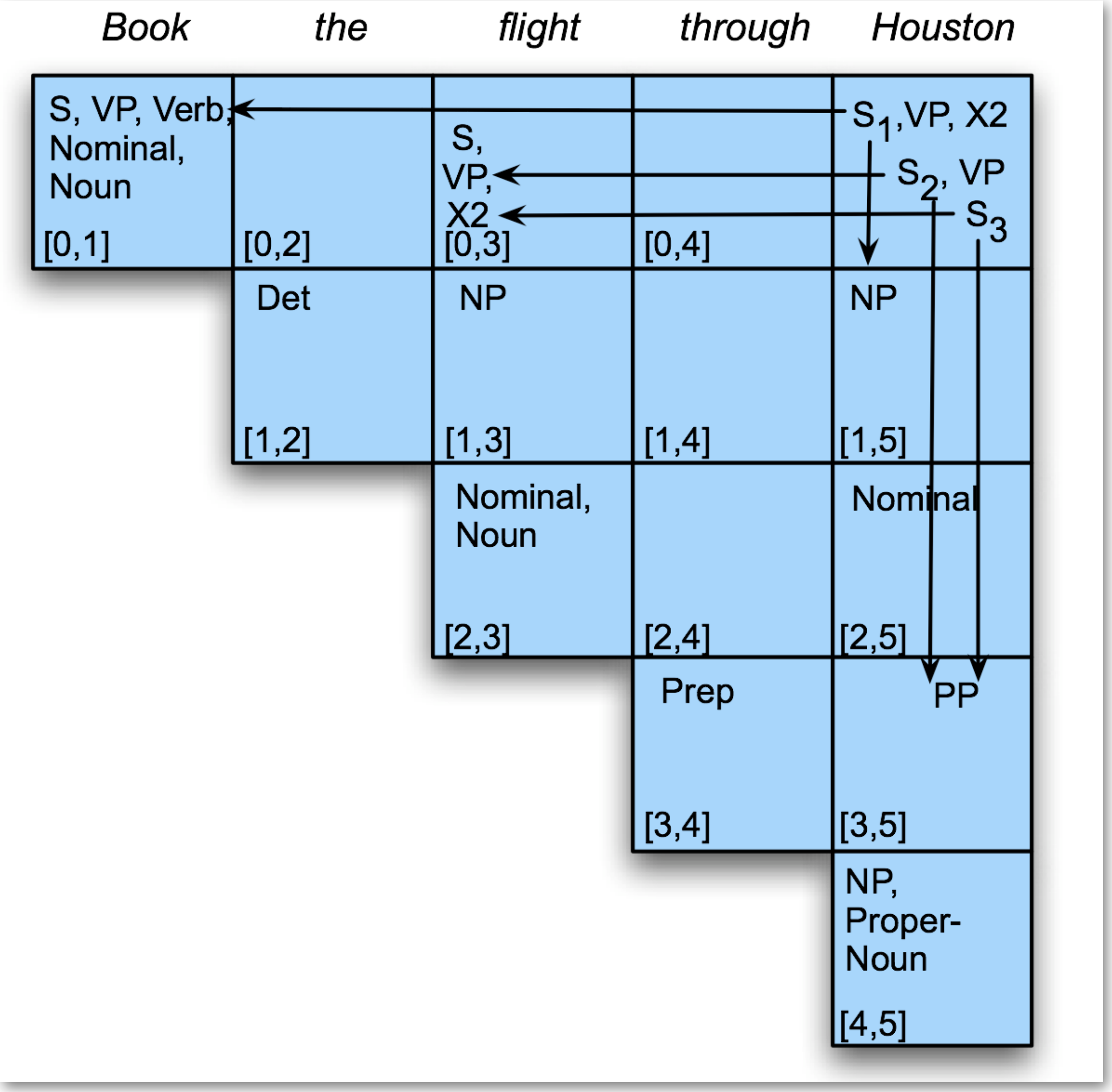
# Example


Book
the
flight
through
Houston
S, VP, Verb, Nominal, Noun
[0,1]
[0,2]
S,VP,X2
[0,3]
[0,4]
[0,5]
Det
[1,2]
NP
[1,3]
[1,4]
NP
[1,5]
Nominal, Noun
[2,3]
[2,4]
Nominal
[2,5]
Prep
[3,4]
PP
[3,5]
NP, Proper-Noun
[4,5]

# Example

| *Book* | *the* | *flight* | *through* | *Houston* |
| --- | --- | --- | --- | --- |
| S, VP, Verb, Nominal, Noun [0,1] | [0,2] | S,VP,X2 [0,3] | [0,4] | [0,5] |
| | Det [1,2] | NP [1,3] | [1,4] | NP [1,5] |
| | | Nominal, Noun [2,3] | [2,4] | Nominal [2,5] |
| | | | Prep [3,4] | PP [3,5] |
| | | | | NP, Proper-Noun [4,5] |

# Example



Book
the
flight
through
Houston
S, VP, Verb, Nominal, Noun
[0,1]
[0,2]
S, VP, X2
[0,3]
[0,4]
S1, VP, X2
S2, VP
S3
Det
[1,2]
NP
[1,3]
[1,4]
NP
[1,5]
Nominal, Noun
[2,3]
[2,4]
Nominal
[2,5]
Prep
[3,4]
PP
[3,5]
NP, Proper-Noun
[4,5]

# CKY Notes

- Since it's bottom up, CKY populates the table with a lot of phantom constituents.
  - Segments that by themselves are constituents but cannot really occur in the context in which they are being suggested.
  - To avoid this we can switch to a top-down control strategy
  - Or we can add some kind of filtering that blocks constituents where they can not happen in a final analysis.

# Earley Parsing

- Allows arbitrary CFGs
- Top-down control
- Fills a table in a single sweep over the input
  - Table is length N+1; N is number of words
  - Table entries represent
    - Completed constituents and their locations
    - In-progress constituents
    - Predicted constituents

# States

- The table-entries are called states and are represented with dotted-rules.

| | |
|---|---|
| $S \rightarrow \cdot\ VP$ | A VP is predicted |
| $NP \rightarrow Det \cdot Nominal$ | An NP is in progress |
| $VP \rightarrow V\ NP \cdot$ | A VP has been found |

# States/Locations

- $S \rightarrow \bullet\, VP\ [0,0]$
- A VP is predicted at the start of the sentence
- $NP \rightarrow Det \bullet Nominal\ [1,2]$
- An NP is in progress; the Det goes from 1 to 2
- $VP \rightarrow V\ NP\ \bullet\ [0,3]$
- A VP has been found starting at 0 and ending at 3

# Earley

- As with most dynamic programming approaches, the answer is found by looking in the table in the right place.
- In this case, there should be an S state in the final column that spans from 0 to N and is complete. That is,
  - $S \rightarrow \alpha \bullet [0,N]$
- If that's the case you're done.

# Earley

- So sweep through the table from 0 to N…
  - New predicted states are created by starting top-down from S
  - New incomplete states are created by advancing existing states as new constituents are discovered
  - New complete states are created in the same way.

# Earley

- More specifically…
  1. Predict all the states you can upfront
  2. Read a word
     1. Extend states based on matches
     2. Generate new predictions
     3. Go to step 2
  3. When you’re out of words, look at the chart to see if you have a winner

# Core Earley Code

```
function EARLEY-PARSE(words, grammar) returns chart

  ENQUEUE((γ → • S, [0,0]), chart[0])
  for i ← from 0 to LENGTH(words) do
   for each state in chart[i] do
     if INCOMPLETE?(state) and
               NEXT-CAT(state) is not a part of speech then
        PREDICTOR(state)
     elseif INCOMPLETE?(state) and
               NEXT-CAT(state) is a part of speech then
        SCANNER(state)
     else
        COMPLETER(state)
   end
  end
  return(chart)
```

# Earley Code

**procedure** PREDICTOR($(A \rightarrow \alpha \bullet B\, \beta,\ [i,j])$)
    **for each** $(B \rightarrow \gamma)$ **in** GRAMMAR-RULES-FOR($B$, *grammar*) **do**
        ENQUEUE($(B \rightarrow \bullet\, \gamma,\ [j,j])$, *chart*[$j$])
    **end**

**procedure** SCANNER($(A \rightarrow \alpha \bullet B\, \beta,\ [i,j])$)
    **if** B $\subset$ PARTS-OF-SPEECH(*word[j]*) **then**
        ENQUEUE($(B \rightarrow word[j],\ [j, j+1])$, *chart[j+1]*)

**procedure** COMPLETER($(B \rightarrow \gamma \bullet,\ [j,k])$)
    **for each** $(A \rightarrow \alpha \bullet B\, \beta,\ [i,j])$ **in** *chart*[$j$] **do**
        ENQUEUE($(A \rightarrow \alpha\, B \bullet \beta,\ [i,k])$, *chart[k]*)
    **end**

# Example

- Book that flight
- We should find… an S from 0 to 3 that is a completed state…

# Chart[0]

| | | | |
|---|---|---|---|
| S0 | $\gamma \rightarrow \bullet S$ | [0,0] | Dummy start state |
| S1 | $S \rightarrow \bullet NP\ VP$ | [0,0] | Predictor |
| S2 | $S \rightarrow \bullet Aux\ NP\ VP$ | [0,0] | Predictor |
| S3 | $S \rightarrow \bullet VP$ | [0,0] | Predictor |
| S4 | $NP \rightarrow \bullet Pronoun$ | [0,0] | Predictor |
| S5 | $NP \rightarrow \bullet Proper\text{-}Noun$ | [0,0] | Predictor |
| S6 | $NP \rightarrow \bullet Det\ Nominal$ | [0,0] | Predictor |
| S7 | $VP \rightarrow \bullet Verb$ | [0,0] | Predictor |
| S8 | $VP \rightarrow \bullet Verb\ NP$ | [0,0] | Predictor |
| S9 | $VP \rightarrow \bullet Verb\ NP\ PP$ | [0,0] | Predictor |
| S10 | $VP \rightarrow \bullet Verb\ PP$ | [0,0] | Predictor |
| S11 | $VP \rightarrow \bullet VP\ PP$ | [0,0] | Predictor |

Note that given a grammar, these entries are the same for all inputs; they can be pre-loaded.

# Chart[1]

| | | | |
|---|---|---|---|
| S12 | $Verb \rightarrow book \bullet$ | [0,1] | Scanner |
| S13 | $VP \rightarrow Verb \bullet$ | [0,1] | Completer |
| S14 | $VP \rightarrow Verb \bullet NP$ | [0,1] | Completer |
| S15 | $VP \rightarrow Verb \bullet NP\ PP$ | [0,1] | Completer |
| S16 | $VP \rightarrow Verb \bullet PP$ | [0,1] | Completer |
| S17 | $S \rightarrow VP \bullet$ | [0,1] | Completer |
| S18 | $VP \rightarrow VP \bullet PP$ | [0,1] | Completer |
| S19 | $NP \rightarrow \bullet Pronoun$ | [1,1] | Predictor |
| S20 | $NP \rightarrow \bullet Proper\text{-}Noun$ | [1,1] | Predictor |
| S21 | $NP \rightarrow \bullet Det\ Nominal$ | [1,1] | Predictor |
| S22 | $PP \rightarrow \bullet Prep\ NP$ | [1,1] | Predictor |

# Charts[2] and [3]

| | | | |
|---|---|---|---|
| S23 | $Det \rightarrow that \bullet$ | [1,2] | Scanner |
| S24 | $NP \rightarrow Det \bullet Nominal$ | [1,2] | Completer |
| S25 | $Nominal \rightarrow \bullet Noun$ | [2,2] | Predictor |
| S26 | $Nominal \rightarrow \bullet Nominal\ Noun$ | [2,2] | Predictor |
| S27 | $Nominal \rightarrow \bullet Nominal\ PP$ | [2,2] | Predictor |
| S28 | $Noun \rightarrow flight \bullet$ | [2,3] | Scanner |
| S29 | $Nominal \rightarrow Noun \bullet$ | [2,3] | Completer |
| S30 | $NP \rightarrow Det\ Nominal \bullet$ | [1,3] | Completer |
| S31 | $Nominal \rightarrow Nominal \bullet Noun$ | [2,3] | Completer |
| S32 | $Nominal \rightarrow Nominal \bullet PP$ | [2,3] | Completer |
| S33 | $VP \rightarrow Verb\ NP \bullet$ | [0,3] | Completer |
| S34 | $VP \rightarrow Verb\ NP \bullet PP$ | [0,3] | Completer |
| S35 | $PP \rightarrow \bullet Prep\ NP$ | [3,3] | Predictor |
| S36 | $S \rightarrow VP \bullet$ | [0,3] | Completer |
| S37 | $VP \rightarrow VP \bullet PP$ | [0,3] | Completer |

# Efficiency

- For such a simple example, there seems to be a lot of useless stuff in there.
- Why?

• It's predicting things that aren't consistent with the input

• That's the flipside to the CKY problem.

# Details

- As with CKY that isn't a parser until we add the backpointers so that each state knows where it came from.

# Back to Ambiguity

- Did we solve it?

# Ambiguity

- No…
  - Both CKY and Earley will result in multiple S structures for the [0,N] table entry.
  - They both efficiently store the sub-parts that are shared between multiple parses.
  - And they obviously avoid re-deriving those sub-parts.
  - But neither can tell us which one is right.

# Ambiguity

- In most cases, humans don’t notice incidental ambiguity (lexical or syntactic). It is resolved on the fly and never noticed.
- We’ll try to model that with probabilities.
- But note something odd and important about the Groucho Marx example…